MODELING OF THE PROPOSED ATA FAST CORRECTION COILS*

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Abstract

The Fast Correction Coil system will provide dynamic beam steering on the ATA linear electron accelerator at LLNL. We are designing the system using multi-conductor transmission line theory to model the coil response. The JASON electrostatics code is used to predict both **E** and **B** field profiles within the coil and to determine all coil electrical parameters. We simulate the electrical system behavior using either of two circuit models based on these parameters. One incorporates the NET2 circuit analysis code, while the other is a purely analytic model. These models have allowed us to conduct a comprehensive trade-off study aimed at designing the most efficient system within the constraints set by accelerator physics requirements.

Introduction

The Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory is capable of producing a pulsed 10 MeV electron beam of 6 KA peak current over the pulse flat top duration of 40 nsec. During each pulse, the beam position will vary within a ±0.5 mm window. We are designing a Fast Correction Coil (FCC) system which will dynamically apply beam steering during the pulse duration. Our goal is to reduce the beam offset by a factor of five over nominal conditions.[1]

Two fast correction coils will provide both positional and angular steering in any desired direction. Each coil is made up of steering bars located inside of the beampipe as shown in Figure 1. Due to the high bandwidth (40 MHz) of the correction signal, steering fields must be generated inside of the pipe; there is not sufficient time for appreciable magnetic diffusion through the pipe wall or the bars themselves. As a result of this geometry, we are able to model the "coil" as a lossless multi-conductor transmission line. Both transverse magnetic and electric fields within the line steer the electron beam. The coil dimensions are sufficiently small compared to wavelength to prevent higher order modes from being excited.

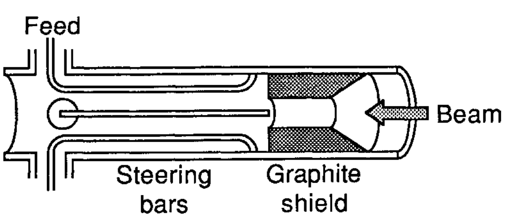

Figure 1. Fast Correction Coil in ATA beamline. A coil with four steering bars is shown. Graphite shield prevents electron beam from striking bars.

Individual steering bars are fed downstream of the beam by coaxial cables. The upstream ends of the bars can be shorted to the wall as shown in Figure 1 or terminated in some chosen impedance. To design the coils, we must optimize the coil dimensions depicted in Figure 2, the number of steering bars to be used, and the feed coax and termination impedances. Equal angular spacing of bars is required to facilitate beam steering in all directions.

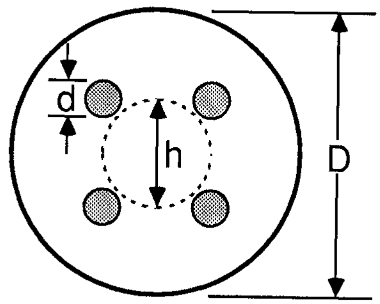

Figure 2. Coil cross section. D = beampipe I.D., d = steering bar diameter, and h = clear space diameter.

Field Modeling

We use the JASON electrostatics simulation code and multi-conductor transmission line theory to determine the electromagnetic characteristics of the coil.[2] Since only TEM modes are present, JASON accurately predicts the **E** fields inside of the beampipe in the coil region. The correction coil dielectric is vacuum with the exception of supports and feeds for each steering bar. **B** inside the coil is related to **E** by free space parameters. The magnetic flux lines follow the same path as the equipotentials plotted by JASON. Figure 3 depicts three of the four wave propogation modes in the coil which we have modeled.

Coil Impedances

Propagation velocity is c for all modes, but each mode has its own characteristic impedance determined by coil geometry. We can relate these characteristic impedances to the interconductor capacitances using multi-conductor transmission line theory.[3] If Z_{ij} is the equivalent impedance that a traveling wave sees between two conductors, the per-length capacitance between the conductors is given by:

$$C_{ij} = \frac{1}{cZ_{ij}} \qquad (1)$$

c is lightspeed in vacuum. We use the JASON postprocessor, JCALC, to determine the mutual capacitances of the steering bars.[4] JCALC calculates the electrostatic field energy contained within a JASON simulation mesh. For a particular problem configuration, capacitance is given by $E=1/2\ CV^2$. Equation 1 is then used to obtain characteristic impedance values.

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14. ABSTRACT
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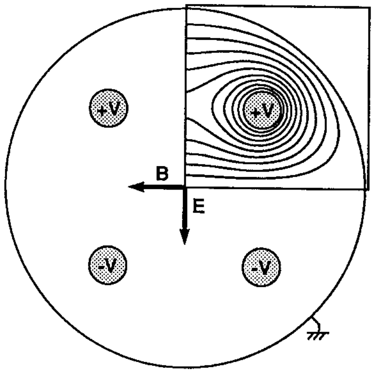

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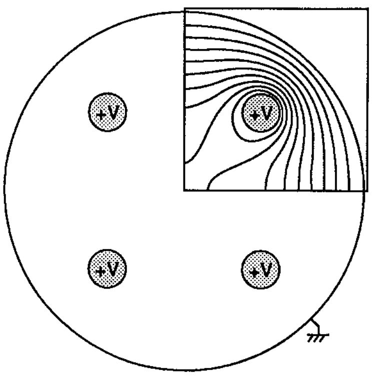

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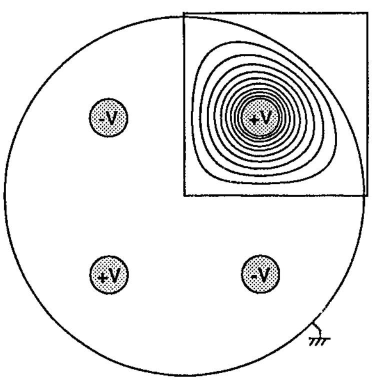

(c)

Figure 3. Independent traveling wave modes in a coil with four steering bars. Three are shown. The fourth mode would be a 90° rotation of the mode shown in (a). Propogation is into the plane of the page.

In Figure 4, we express the characteristic impedances of a symmetric four bar steering coil in terms of Z_a, Z_b, and Z_c. To generate a proper steering field on axis demands that steering bars 180° apart be driven at opposite polarity. We find that this additional requirement allows us to fold impedances Z_b and Z_c into Z_a, which we then rename Z_0. As long as the condition of opposite polarities is satisfied, the characteristic impedance Z_0 seen at each steering bar is equivalent. We have generated Figure 5 to help determine design trade-offs for a four bar coil.

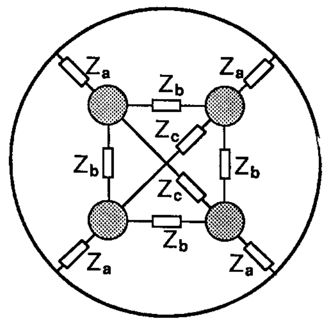

Figure 4. Characteristic impedances seen by traveling waves in a symmetric four bar steering coil. For a matched FCC system, these are the impedances appearing at the coil terminals.

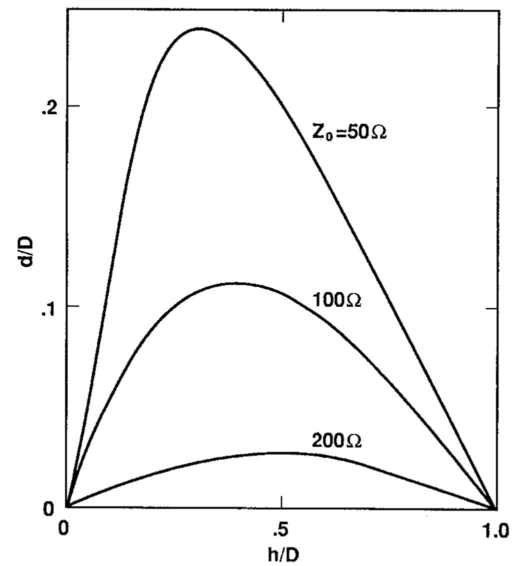

Figure 5. Characteristic impedances resulting from a range of four bar coil geometries. Impedance Z_0 is measured between each steering bar and the beampipe for the drive conditions given in the text. Impedance drops as the bars approach each other or the beampipe wall.

Field Uniformity

JASON is also used to predict the spacial variation in the steering field to insure that it exhibits sufficient uniformity to prevent beam dispersion. We arbitrarily define field uniformity as the fractional decrease in **B** for the mode shown in Figure 3a as the measurement point moves radially upward from the axis. Figure 6 presents a comparison for several coil configurations with Z_0= 100 Ω. Not surprisingly, field uniformity improves as the steering bars are moved away from the beam region. We will show that this improvement must be traded off against an increased coil power requirement. Increasing the number of steering bars allows better uniformity at lower power levels, but this greatly increases the complexity of the FCC control system and associated hardware.

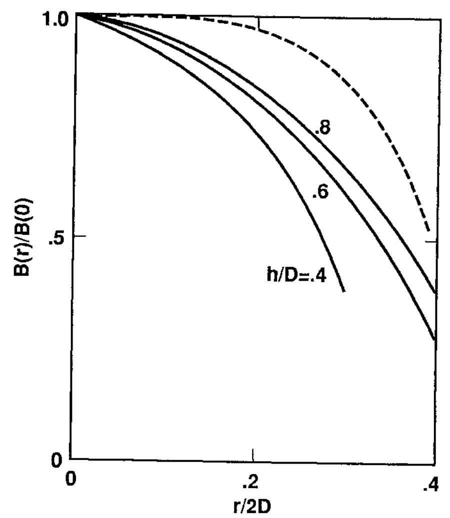

Figure 6. Field uniformity, expressed as the fractional decrease in B as the measurement point moves a distance r off axis. Characteristics of several four bar coil configurations are given by the solid lines. The broken line represents an eight bar coil with h/D = 0.4. All have Z_0=100 Ω impedance seen at each steering bar.

Power Requirements

The coil power requirement depends on a number of design parameters, most obviously coil geometry. Impedance mismatch between Z_0 for the steering bars and the feed and termination impedances also affects electrical efficiency. A mismatched system allows field energy to remain in the correction coil for a longer time than for a matched system, but bandwidth is adversely affected. We have calculated on-axis **B** field per unit power for a number of matched systems. Efficiency of unmatched systems can be extrapolated from this data using circuit theory. Figure 7 gives the results for three different four bar coil geometries. We find that steering bar location has a much greater effect on electrical efficiency than Z_0 for $Z_0 > 100$ Ω. Moving the bars close to the beampipe wall concentrates field energy near the wall rather than on axis where steering field is needed.

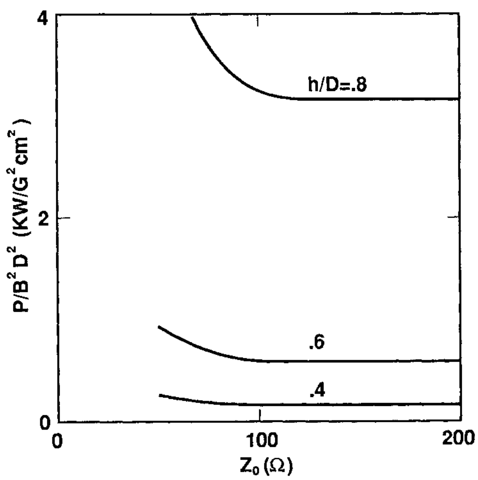

Figure 7. Electrical efficiency of four bar coil designs. P is the power input needed to produce the wave mode shown in Figure 3a in a matched correction coil. **B** is the resulting on-axis steering field.

Beam-Induced Voltages on Steering Bars

We are concerned about voltages induced on the FCC steering bars due to the 6 KA e-beam current and the effect this would have on the coil drive circuits. One would guess that this voltage could be reduced by moving the bars outward toward the beampipe wall, thereby decreasing the magnetic flux linked between bar and wall. Calculational results shown in Figure 8 depict this trend. Steering bar size increases with decreasing Z_0, which also results in a lower linkage of beam generated flux. The coupling is calculated using a version of JASON which has been modified to handle a limited class of 2D magnetostatic field problems. JASON produces **B**, and vector potential, **A**. Linked flux, ϕ , is given by:[5]

$$\phi = \oint_C \mathbf{A} \cdot d\mathbf{l} \tag{2}$$

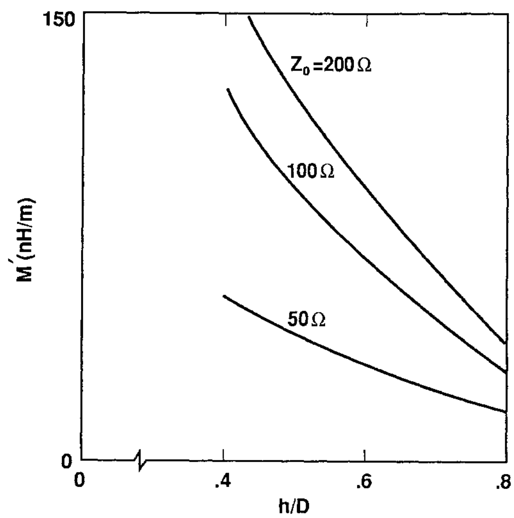

Figure 8. Magnetic coupling between electron beam current and the loop formed by each steering bar and the bêampipe wall. M' is the per-length mutual inductance for various four bar coil configurations.

Circuit Modeling

We have two circuit models of the Fast Correction Coil system which incorporate the transmission line model of the coil. One is a computer simulation using the NET2 circuit analysis code. The coil is modeled as a lumped-parameter line using the interconductor capacitances and inductances we have calculated using JASON/JCALC. The second model is an analytic derivation based on traveling wave modes within the coil and mode coupling at the steering bar feed points and terminations. Traveling waves within the coil are assumed to propagate at velocity c without loss. Reflection and transmission matrices are formulated to characterize mode coupling.

We compared results from both models with data from the two bar coil prototype shown in Figure 9. Operation of the pulser induces a voltage in the undriven steering bar which is viewed by the oscilloscope. Agreement between the peak induced voltage predicted by the models and that seen experimentally is within 10%.

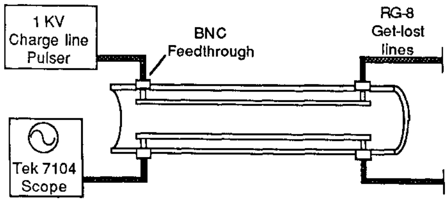

Figure 9. Two bar correction coil system with D = 15cm, d/D = 0.16, and h/D = 0.5. Z_0= 69 Ω , resulting in a moderate mismatch with the 50 Ω feedlines and terminations. This test was constructed to validate the models and does not represent any final FCC configuration.

Conclusions

Dynamic beam steering devices like the proposed fast correction coils can be modeled as lossless multi-conductor transmission lines. A 2D electrostatics code will simulate the **E** and **B** field patterns of the various traveling wave modes within the coil. Field energies can be used to calculate the characteristic impedances of the transmission line structure, as well as per-length interconductor capacitances and inductances. These electrical parameters form the basis for circuit modeling of the entire FCC system including feed lines and terminations. Circuit modeling provides important information on the behavior of systems where mismatch occurs at the coil feeds and terminations. Either a standard circuit analysis code like NET2 or a method based on reflection and transmission matrices can be used.

Important design trade-offs can be made by further analysis of the 2D **E** and **B** field simulations. Specifically, we find that steering bar impedances decrease as the bars approach either each other or the beampipe inner wall. Field uniformity near the beampipe axis increases as the bars approach the wall, but at a marked expense in electrical efficiency. Moving the bars toward the wall reduces voltages induced in the steering bars by the electron beam.

The ensemble of models has allowed us to generate a baseline fast correction coil design. The baseline coil is described in an accompanying paper (reference 1).

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